LUNAR DISSIPATION: ROTATIONAL AND ORBITAL CONSEQUENCES

J. G. Williams , T. P. Krisher, D. H. Boggs, J. T. Ratcliff, and J. O. Dickey
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109

The analysis of lunar laser ranging (LLR) data strongly detects a signature of dissipation in lunar rotation. The two possible sources of dissipation are solid-body tides and interaction at a liquid-core/solid-mantle interface. A simultaneous fit of both dissipation models [1] finds each cause contributing about half of the dissipation signature. The separation comes from rotation terms which are a few percent of the leading dissipation term. Dissipation from tides and core also influences the lunar orbit, causing secular changes in the orbit period and eccentricity. The latter is useful and is in better agreement when core dissipation is included.

The lunar equator (mantle) is tilted I = 1.5427° to the ecliptic plane and it exhibits retrograde precession along the ecliptic with an 18.6 yr period. The equator and orbit planes precess along the ecliptic plane with the same 18.6 yr (retrograde) period. Without dissipation, the descending node of the equator matches the ascending node of the orbit. The most important effect of dissipation on the lunar rotation is a shift of the node of the precessing equator plane (and pole of rotation) from alignment with the orbit node [2] [3] [4]. Dissipation from both solid-body tides [2] and core/mantle interactions [3] can cause this phase shift. The shift is most sensitive to monthly tides and monthly velocity differences between fluid core and mantle. The shift in the precessing pole direction projects into the direction to Earth as a monthly signature.

The most recent LLR data can be fit with a 2 cm rms residual. The observed dissipation signature is a shift of the pole of rotation by 0.26" (or 9.8" for the intersection of the equator and the ecliptic planes), and it is strongly observed in the LLR data. This shift gives the dissipation at a one month period. For the results in [1] the tidal signature corresponds to a specific dissipation Q of 60 and the core dissipation corresponds to a small core (roughly 300 km radius for the density of iron and turbulent interaction). In addition to the strong monthly signature, a weak annual tidal signature is detected.

Lunar rotational changes (lunar physical librations) can be split into longitude (rotation angle about the polar axis) and latitude (either two pole direction coordinates or two Euler angles) effects. The separation of different sources of dissipation and the determination of Q's at tidal periods other than a month requires distinguishing small signatures at different periods. Theoretical computations of these small signatures have been carried out for both tidal and fluid core models.

For the fluid-core dissipation computation, a spherical core is assumed. The shift of the mantle's pole direction dominates other effects. There is an order-of-magnitude smaller constant shift in the longitude angle. Other longitude and latitude terms are too small to be useful. For the core rotation, the core's equator should be tilted to the ecliptic plane by a few arc minutes, and should precess with the 18.6 yr period. The coupling between the core and mantle is too weak to make the core's rotation pole align with the mantle's pole. The core rotates about 0.04% slower than the mantle.

Dissipation due to tides provides more variety. The shift in the precessing pole direction and a constant longitude shift are the biggest terms. For the longitude angle, important periodic terms occur at 1095 d, 365 d, and 206 d. In coordinates rotating with the Moon, the large pole shift is monthly (27.2 d) and another latitude term occurs at 2190 d. Additional terms were computed, but they are too small to detect with existing range data.

Tidal distortions of the Moon occur at different frequencies. While one can assume that the Love numbers will show little variation for different tidal frequencies, the tidal Q's may be frequency dependent. Consequently, the coefficient of each periodic rotation term is developed as a linear combination of inverse Q's for tidal frequencies. Thus, the rotation coefficients can be calculated for any postulated rule for Q vs frequency, or measurements of the periodic terms can be inverted to give more than one Q. The dominant latitude term depends most strongly on the Q at 27.2 d. The annual longitude term depends mainly on an annual Q. The 1095 d term depends on several monthly Q's, plus a 1095 d Q.

When analyzing range data, a constant change in the rotational longitude angle cannot be fit geometrically because the selenocentric longitude of each of the retroreflectors is also a free parameter. A change in one angle counteracts the other. The five periodic terms must provide the separation during fits. However, the tidal variations of the gravity field and the longitude shift of the permanent gravity-field direction both influence the orbit. Changes in orbital period and eccentricity result. Tides on the Earth also influence the same orbit parameters. Earth tides are two orders-of-magnitude more effective than lunar tides at changing orbit period, making it difficult to separate out the lunar contribution with useful accuracy. The eccentricity rate is more balanced. Eccentricity rate is a usable test of the source of dissipation in the Moon. LLR fits of eccentricity rate favor some core contribution to dissipation over pure tidal dissipation.

There are rotational and orbital consequences of dissipation in the Moon. Separating tidal from fluid core influences during fits of the lunar laser ranges requires both accurate data and accurate models. In addition to solid-body tides, a fluid core remains an attractive explanation for the dissipation in the Moon.

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